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Enhancement of the *c*-axis texture of aluminum nitride by an inductively coupled plasma reactive sputtering process

C.-M. Yeh[a], C.H. Chen[a], J.-Y. Gan[a], C.S. Kou[b], J. Hwang[a,*]

[a]Department of Material Science and Engineering, National Tsing Hua University, Hsin-Chu City, Taiwan, Republic of China
[b]Department of Physics, National Tsing Hua University, Hsin-Chu City, Taiwan, Republic of China

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Abstract

Inductively coupled plasma reactive sputtering technique has been applied to grow highly oriented aluminum nitride on Si(111) at high process pressure. An inductive coil of 3 and 1/4 turns was introduced to generate a plasma zone near the substrate holder, which provides additional energy to the radicals inside the plasma zone. The full width at half-maximum of the X-ray rocking curve of AlN(0002) is reduced from 7.90° to 4.05° when the inductive coil power is raised from 0 to 180 W. The enhancement of the *c*-axis texture of AlN is attributed to the increase of the density of the sputtered Al atoms of high energy.

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Keywords: Plasma deposition; Texture; Sputterring

1. Introduction

Aluminum nitride (AlN) has received much attention in the electro-acoustic devices, such as surface acoustic wave (SAW) device and thin film bulk acoustic wave resonator (FBAR), since it exhibits high ultrasonic velocity [1,2], large electromechanical coupling factor [3,4], small transmission loss [5,6] and high temperature stability [7]. One of the major research topics is to improve the AlN film quality by enhancing its c-axis texture and surface smoothness which are two key characters useful in the SAW and FBAR applications. Radio-frequency reactive magnetron sputtering (RMS) is the most frequently used technique in the fabrication of highly c-axis oriented AlN film with smooth surface, in which radio-frequency (RF) power is transmitted to the Al target and generates nitrogen (or nitrogen/argon) plasma to sputter Al onto the substrate. The sputtered Al neutral atoms or radicals may react with the nitrogen radicals to form an AlN film, and as a consequence "reactive sputtering" is used to describe the reactive deposition process. One way to increase the c-axis texture of AlN in the reactive sputtering process is to raise the surface mobility of the deposited Al atoms or AlN particles by increasing the substrate temperature. However, low temperature process is the trend in the development of AlN film technologies since it is easier in the back-end process and more compatible to IC technologies [8]. Another way to increase the c-axis texture is to raise the impingement energy of the sputtered Al atoms, which is primarily achieved by reducing the process pressure [9]. The strategy to raise the impingement energy of the sputtered Al atoms is to eliminate the scattering events by increasing its mean free path that can be achieved at low process pressure. Experimental results indicate that the full width at half-maximum (FWHM) of the X-ray rocking curve of AlN(002) grown at low process pressure (1–3 mTorr) is about 1–3° [10–12]. In contrast, the FWHM of the X-ray rocking curve of AlN(002) grown at high process pressure (~10 mTorr) is as large as 10–15° [13,14]. The elimination of scattering events is indeed effective by

* Corresponding author. Tel.: +886 357 225 77; fax: +886 357 223 66.
E-mail address: jch@mse.nthu.edu.tw (J. Hwang).

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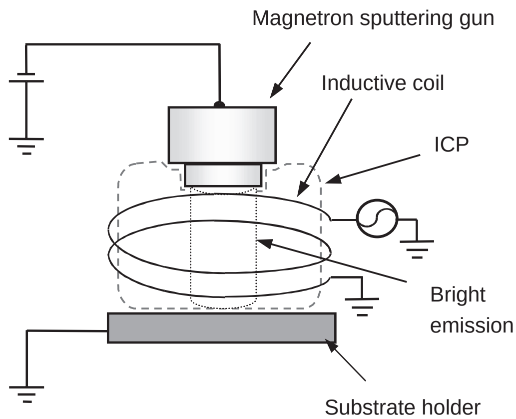

Fig. 1. Schematic of the inductively coupled plasma reactive magnetron sputtering (ICP-RMS) system.

reducing process pressure from ~10 to ~3 mTorr. However, one drawback in the deposition at low process pressure is the existence of large compressive stress in the deposited AlN film [15–17]. When the process pressure increases, compressive stress reduces in magnitude and becomes small tensile stress at ~10 mTorr [15].

In the present work, we attempt to look for an alternative AlN fabrication process to raise the impingement energy of the sputtered Al atoms at high process pressure (~10 mTorr). The new AlN fabrication process is carried out in an "inductively coupled plasma reactive magnetron sputtering (ICP-RMS)" system which consists of a tunable inductive coil power to assist plasma generation. The internal inductive coil power supplies additional energy directly onto the sputtered Al atoms before arriving to the substrate. This helps to enhance the c-axis texture of the AlN film.

2. Experimental details

Aluminum nitride thin films were deposited on Si(111) wafers in an inductively coupled plasma reactive magnetron sputtering (ICP-RMS) system shown in Fig. 1. In this system, the 4-in. diameter internal inductive coil of 3 and 1/4 turns was placed between Al target and the substrate holder and the Al sputtering gun was immerged in the inductive coil by 1 cm. The system was pumped down to a base pressure less than 2×10^{-6} Torr before admitting gas in. The nitrogen and argon gases monitored by mass flow controllers were mixed at a $N_2/(N_2+Ar)$ ratio of 75% before introducing into the chamber. The total pressure was kept at 10 mTorr and the substrate temperature at 350 °C during deposition. The inductive coil at different coil power (0–180 W) generated the ICP plasma during deposition with its reflection power below 1%. The film thickness and surface morphology of AlN thin films were measured by a JEOL JSM-6330F field emission scanning electron microscope (FESEM). A Rigaku RU-H3R X-ray diffractometer with Cu K_α radiation was adopted to perform X-ray rocking curve measurements. An optical emission spectroscopy (OES) was used to detect the chemical species in the plasma, with the wavelength resolution of 0.1 nm in the range of wavelength from 200 to 800 nm.

3. Results and discussion

The deposition rate of AlN can be affected by the inductive coil power. Fig. 2 shows the cross-sectional SEM micrographs of AlN thin films deposited at various inductive coil powers and a fixed RF magnetron gun power of 350 W. The thickness of the AlN film increases from 1.09 to 1.32 ìm when the inductive coil power increases from 0 to 180 W. The deposition rate increases by a factor of ~21%, which can be well explained by the enhancement of the sputter rate of Al target due to the inductive coil power. When the inductive coil power is on, the Al target is sputtered by the argon and nitrogen ions not only from the electron confined area outside the RF magnetron gun but also from the additional plasma zone generated by the inductive coil power. The existence of the additional plasma zone can be seen directly from the window of the ICP-RMS chamber. When the inductive coil power increases from 0 to 180 W, the glow discharge has a bright emission structure changing from a ring structure to a cylindrical zone under the Al target.

The c-axis texture qualities of the AlN films can be extracted from the X-ray rocking curves shown in Fig. 3.

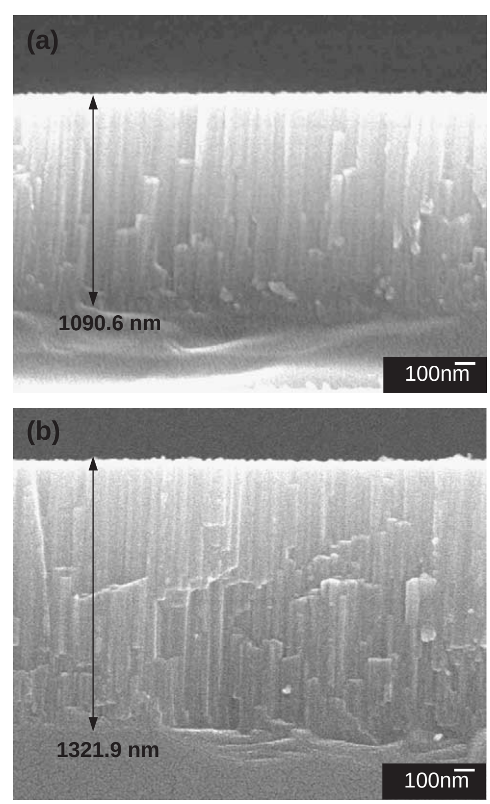

Fig. 2. Cross-sectional SEM images of AlN deposited at different inductive coil power. (a) 0 W, (b) 180 W.

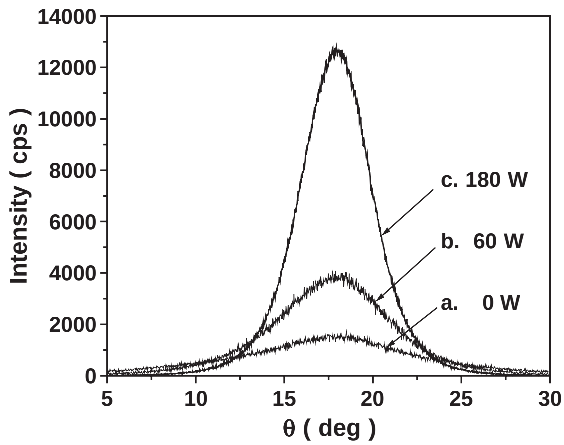

Fig. 3. X-ray rocking curves of AlN deposited at different inductive coil power.

The full width at half-maximum (FWHM) of the X-ray rocking curve of AlN(0002) reduces from 7.90° to 4.05° when ICP power increases from 0 to 180 W. The improvement of c-axis texture can be well explained by the population increase of the sputtered Al atoms at high energy, which is described as follows. The introduction of the inductive coil power into the ICP-RMS system can affect the density of ions and radicals inside the plasma. Fig. 4 shows the optical emission spectrum (OES) of Ar/N_2 plasma ranging from 360 to 430 nm at different inductive coil power and at a fixed RF magnetron gun power of 350 W. By indexing the emission peaks [18], the major chemical species detected in the plasma are ions (N_2^+, Ar^+) and radicals (N_2*, Ar*, Al*). The Al* radical peak (396.15 nm) increases by more than ~25%, and all the other peaks increase in intensity by a factor of ~25% when the inductive coil power is changed from 0 W to 180 W. Two possible physical reasons can explain the higher peak intensity of Al* radical. First, Al* radical is more likely to exist since its excitation energy is lower than that of the N* or Ar* one. Second, the density of Al atoms sputtered from the target also increases with increasing the inductive coil power (Fig. 4).

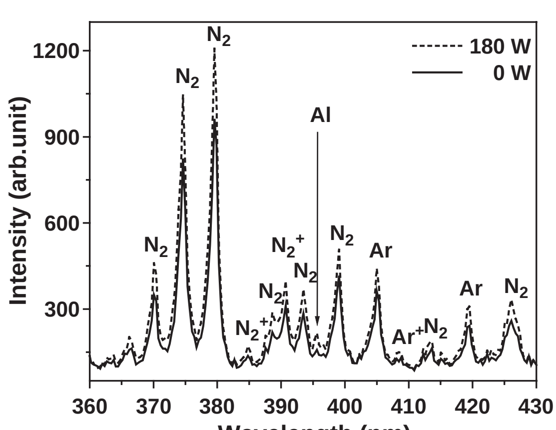

Fig. 4. Optical emission spectra of the Ar/N2 plasma generated at different inductive coil power.

Note that the energy distribution of the Al atoms sputtered from the target varies in a broad range with a peak maximum at low energy and a tail at high energy [9]. It is very reasonable to assume that the energy distribution of the sputtered Al atoms keeps the same shape when the density of the sputtered Al atoms is raised by the inductive coil power. In other words, the inductive coil power provides a way to raise the densities of the sputtered Al atoms at low and high energies. As mentioned earlier, Iriarte et al. reported that the sputtered Al atoms with high energy could enhance the c-axis texture of AlN [9]. Very probably, the increase of the density of the sputtered Al atoms at high energy plays a role in the enhancement of the c-axis texture in our case.

Fig. 5(a) shows the X-ray rocking curve of the AlN thin film deposited at an RF magnetron gun power of 530 W. The magnitude of 530 W is exactly the summation of the inductive coil power of 180 W and the RF magnetron gun power of 350 W, which is the condition, used in curve (a), Fig. 3. The FWHM of the X-ray rocking curve of AlN(0002) is 6.31° in Fig. 5 which is much higher than the FWHM of the X-ray rocking curve (a) in Fig. 3. This indicates that the c-axis texture quality of AlN is better when the inductive coil power of 180 W is on. As mentioned

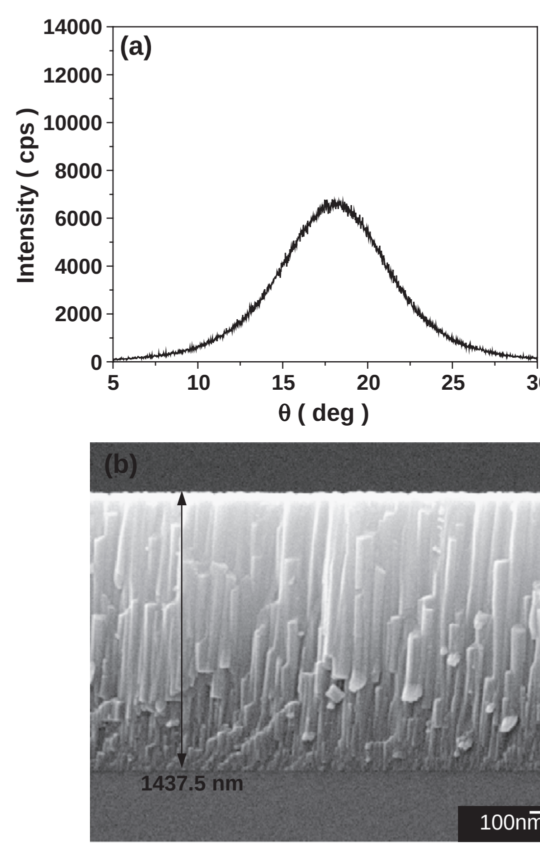

Fig. 5. (a) X-ray rocking curves of AlN deposited at an RF magnetron gun power of 530 W. (b) Cross-sectional SEM images of AlN deposited at a RF magnetron gun power of 530 W.

earlier, the plasma zone generated by the inductive coil power is near the substrate rather than near the Al target. Very probably, the density of the sputtered Al atoms of high energy decay very fast, due to the collisions with gas molecules, during their travel to the substrate in a traditional RMS system. With the help of the inductive coil design, all the sputtered Al atoms can gain energies from the plasma zone generated by the inductive coil power during their travel to the substrate. And the density of the sputtered Al atoms of high energy becomes higher. The c-axis texture of AlN is enhanced as a consequence. However, the enhancement of the c-axis texture by the inductive coil power sacrifices the deposition rate. Fig. 5(b) shows the cross-sectional SEM micrograph of the AlN thin film deposited at an RF magnetron gun power of 530 W. The deposition rate of AlN is 1.43 ìm/h, which is higher than that for the deposition condition in Fig. 2b. The deposition rate becomes higher when the inductive coil power of 180 W is totally re-directed and added to the RF magnetron gun power.

4. Conclusions

Highly c-axis oriented AlN films have been successfully deposited on Si(111) at high process pressure in an ICP-RMS system. The inductive coil power generates a plasma zone closer to the substrate, which can enhance the c-axis texture of AlN. However, the deposition rate of AlN is reduced when the total power is distributed in part to the inductive coil power. The enhancement of the c-axis texture can be explained by the increase of the density of high energy sputtered Al atoms. The role of inductive coil power is to raise the impingement energy of all the sputtered Al atoms without reducing process pressure. The new ICP-RMS fabrication process provides a new way to grow AlN films of high c-axis texture at high pressure.

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